

OPTICAL MINERALOGY

Elements of optics

Nature of light: Visible light, as part of the electro-magnetic spectrum, travels in a straight line with a transverse wave motion; i.e. to vibrate at right angles to the direction of propagation (i.e. wave in water)

- Frequency is the number of waves/sec. passing a fixed point.
- Velocity = frequency X wavelength.
- In light waves have wavelength, amplitude, frequency and velocity but their transverse vibrations perpendicular to the direction of propagation, take place in all possible directions.

Reflection:

Law of reflection: a) $\sin i = \sin r$

b) i and r lies in the same plane.

Refraction:

The amount of bending depends on the obliquity of the incident ray and the relative densities of two media: the greater the angle of incidence and the greater the density difference, the greater is the refraction.

Optics of isotropic medium – refractive medium

Index of refraction or Refractive index

Snell's Law:

The ratio of $\sin I : \sin r$ is a constant for any pair of media.

i.e. $\sin i / \sin r = n = \text{constant} = \text{R.I.}$

- Velocity decrease on entering the denser medium
- Velocity of light in air (V)
- Velocity of light in denser medium (v)

$$\text{Ratio } V/v = n$$

Since $V = 1$, $n = 1/v$ or $n = \text{reciprocal of the velocity.}$

- Longer the wavelength greater the velocity
- Red light has greater velocity than violet light

For red is less than n for violet

Greater the velocity lesser the R.I.

Lesser the velocity greater the R.I.

A crystal thus has different RI for different wavelengths of light. This phenomena is known as 'dispersion of the indices' and because of it, monochromatic light (single white light) is used for accurate determination of refractive index.

Total Reflection and Critical Angle:

Light is refracted toward the normal when it passes from a lower to a higher RI medium. When the conditions are reversed, i.e. light moves from higher to the lower index medium, it is refracted away from the normal.

At c' refraction angle is 90^0 , $\angle CON'$ = Critical angle,
D' – Total Reflection

The measurement of the critical angle is a quick and easy method of determining the R.I. of both liquids and solids.

Instrument is Refractometer

$N = n \times \text{sine of the critical angle}$, where n = RI of the mineral and N = RI of hemisphere (1.8 to 1.9).

Isotropic and Anisotropic media:

Isotropic: Light moves in all directions with same or equal velocities and hence isotropic minerals have a single refractive index.

Isotropic Materials: Isometric crystals, non-crystalline substances as gases, liquids and glass e.g. Galena, Sphalerite, Garnet, Diamond etc.

Anisotropic: the velocity of light varies with crystallographic directions and hence it has two refractive indices (double refraction). Crystals other than isometric systems are anisotropic.

Anisotropic Substance

Uniaxial (Tetra, Hex)	Biaxial (Ortho, Mono, Tri)		
+ve (Quartz)	-ve (calcite)	+ve (Barite)	-ve (Micas)

Polarization and interference of Light:

When the wave motion of light is confined to vibrations in a single plane, the light is said to be plane polarized and the phenomena is called polarization.

The plane at right angles to the plane of transverse vibration is called the plane of polarization.

Polarization may be accompanied by

1. reflection 2. refraction 3. absorption and 4. double refraction.

Interference of Lights: If two waves of like length and intensity and propagated in the same direction, meet in the same phase, they unite to form a wave of double intensity (double amplitude). This will cause, an increase in the intensity of the light. If, however, the waves differ in phase by half a wavelength or an odd multiple of this, they interfere and extinguish each other and no light results.

(Polarized light by absorption)

Polaroid: Polaroids are polarizing sheets made by aligning crystals on an acetate base. These crystals absorb very little light in one vibration direction but are highly absorptive in the other. The light transmitted by the sheet is thus plane polarized. Because they are thin and can be made in large sheets, manufactured polarizing plates are extensively used in optical equipment, including many polarizing microscopes.

Darkness caused by absorption produced by two superimposed tourmaline xls.

(Polarized light by Double Refraction)

Nicol Prism:

Made by Iceland Spar (transparent calcite)

Name after William Nicol

E-ray with RI close to that of Canada Balsam proceeds essentially undeviated through the prism and emerges as plane polarized light.

Polarizing Microscope - construction and use

(Petrological Microscope)

Eyepiece (5x, 10x, 15x)/ Ocular

Bertrand Lens (for Uniaxial, Biaxial test)

Analyzer (Nicol prism or Polaroid)

Objective (2x, 10x, 40x)

Stage (rotating) with gradation of 0-360⁰

Condenser (convergent lens)

Iris diaphragm

Polarizer (Nicol Prism or Polaroid). Fixed

Mirror (concave/ plane) source of light

- crossed-hairs in ocular in N-S and E-W position
- Polarizer – vibrating in N-S direction
- Analyzer – vibrating in E-W direction
- The polarizer and analyzer are collectively called 'Polars'
- When both polars are in position, they are said to be 'crossed' and if no anisotropic xl is between them, no light reaches the eye.

Magnification and Resolving power:

- Hand lens (magnification 6x or 10x) for examine a mineral, a rock or even a soil prior to microscopic study.
- Binocular microscope with higher magnification for study of thin section by polarizing microscope (30x)
- Reflecting microscope for study the polished opaque minerals.
- Electron microscope for study the finely xline materials.
- X-ray diffraction for study the difficult identification problem.

The microscope is primarily an instrument for magnification. It is therefore to form an idea of the enlargement of the field of view with the lens system available.

Objective power x ocular power
(2x, 10x, 40x) (5x, 10x, 15x)

There are limits of the resolving power of the microscope, even with the best lens systems available. As long as the increase in magnification results in better vision of an object and more definite separation of detail, the magnification may be said to be 'useful'. When the object merely becomes larger without any increase in resolving power, the magnification is "empty".

(Resolving power = The ability of an optical system e.g. microscope, telescope, the eye etc. to produce separate images of objects very close together).

Optical Properties of minerals

Properties under PP Light:

Color and Pleochroism:

Color: Color, when present is a distinctive feature. Deeply colored minerals are most likely to be colored in thin sections. However, pale tints and color patterns are often significant.

Examples:

Sphalerite	Red, brown, yellow
Spinel	Red, brown, yellow, green, blue, black
Rutile	Red, brown, yellow, green, blue, violet, grey

Fluorite	Pink rose, brown, yellow, green, blue, violet
Garnet	Pink rose, brown, yellow, green, black
Tourmaline	Pink rose, brown, yellow, green
Corundum	Pink rose, blue, violet
Staurolite	Pink rose, brown, green
Hypersthene	Pink rose, brown, green
Andalusite	Pink rose
Zircon	Brown, yellow, grey
Biotite	Brown, yellow, green
Apatite	Brown, green, grey, yellow
Augite	Brown, yellow, green, black
Phlogopite	brown
Hornblende	Brown, green
Epidote	Yellow, green, blue
Chlorite	Green, blue
Cordierite	blue

Pleochroism: Isotropic minerals yield no color change as the mineral is rotated. Anisotropic minerals exhibit a change in color in varying degrees as the stage is rotated. The change produced is known as 'pleochroism'. Natural mineral color in thin sections is observed with the polarizer alone. The variation in color resulting from differential absorption.

Examples of pleochroic minerals:

Rutile, tourmaline, corundum, staurolite, hypersthene, zircon, biotite, apatite, titanite, monazite, aegirine-augite, hornblende, cassiterite, sulphur, epidote, phlogopite, actinolite, chlorite etc.

In pleochroic uniaxial minerals light vibrating parallel to the optic axis is one color, whereas light at right angles is another = Dichroic (or dichroism)

Biaxial (ortho, mono, tri) – when colored in thin section, exhibit three different colors = trichroic.

Pleochroic Formula:

Certain non-opaque crystals absorb light differently in different directions of vibration. If tourmaline for example, is examined under the polarizing microscope with the upper polar removed, it will change color on rotation of microscope stage. When the optic axis of the tourmaline is parallel to the plane of vibration of the lower polar, the light is not as strongly absorbed as when the optic axis is at right angles to this plane. The absorption is expressed by the formula E, weak; O, very strong, or $E < O$.

Tourmaline might have the formula $O = \text{buff (moderate orange yellow or light to moderate yellow)}$; $E = \text{neutral grey}$.

3. Perlitic cracks
4. Lithophysae – like patch
5. Flow (with phenocrysts)
6. Banded
7. Colloform
8. Oolitic
9. Pisolitic
10. Organic Structures
11. Microfossil replacement

Cleavage, Parting and Fracture:

In grinding thin sections cleavage planes often develop which appear in the finished section as lines or bands of varying width.

Cleavage in one direction – single plane of cleavage, e.g. muscovite, topaz.

Cleavage in two direction – pyroxenes, amphiboles and feldspars.

Cleavage in three direction – fluorite, anhydrite.

Parting: Some minerals separate only occasionally or break along planes twinning is called parting. It is not always present and may not continue to finer and finer particles.

Fracture: Irregular cracks.

Refractive Index and Relief:

$$RI = \sin i / \sin r = n = \text{constant} = R.I.$$

Relief: Certain minerals stand out strongly in the field of the microscope, others are moderately visible and frequently the mineral is hardly visible at all. This appearance or visibility of outline and surface is described as relief.

Relief is the visibility of a mineral grain within its surrounding medium.

Relatively described as High, Medium, Low

Becke line and its use:

The Becke line (a narrow line of light) as originally defined, refers to a phenomenon associated with a vertical contact of two substances of different indices of refraction observed on the stage of a microscope. The Becke line is seen to best advantage under the microscope when a medium power objective is used and the opening in the sub stage iris diaphragm is partly closed to render the incident light nearly parallel and to reduce the total amount of illumination.

Use: Raising the tube of microscope – Becke line moves towards higher RI zone.

To determine the relative RI of the minerals.

Properties under crossed Polarizers (crossed nicols)

Twining: Twinning can be best seen between crossed nicols. The two halves of the twin, or the two sets of twin lamellae give different polarization colors and extinguish at different angles e.g. plagioclase = polysynthetic twinning

Extinction: When the vibration directions of a section coincide with those of the polarizer and analyzer, assuming them to be crossed, the section appears dark and it is said to be in the position of extinction.

If a section extinguishes when its xlographic axis or axial plane is parallel to one of the planes of vibration of the nicols it is said to show 'parallel extinction'. If on the other hand, no such parallelism exists between the xlographic directions and the directions of vibration in the mineral the section is said to show 'incline or oblique extinction'.

In the case of uniaxial minerals since the vibration directions always lie in some xlographic axial plane, all sections of such minerals will show parallel extinction.

Extinction angle: Angles between an extinction position and a plane, line or edge in a xl or xl fragments.

A characteristic of monoclinic and triclinic (Biaxial) minerals is often a useful diagnostic property. Cleavage surfaces, twin planes, inclusions etc may be used if their xlographic orientations are known.

Monoclinic amphiboles more than 20° , pyroxenes about 40°

4 times dark in 360° rotation.

Interference colors:

Interfere

Analyzer

Two rays leave the mineral plate

Mineral plate (light entering from Polarizer is resolved into two vibrations at rt. Angles (due to anisotropic)

Polarizer

Source of light

Ist, 2nd, 3rd order and so forth.

Interference colors depend on three factors:

- a) crystallographic orientation – different for different system
- b) Thickness of the section – thicker the section the greater will be the amount of double refraction and consequently the higher the order of the interference colors.
- c) Birefringence – The greater the birefringence the higher the order of interference color.

Anomalous Interference colors:

Occasionally minerals normally assumed to be isotropic become anisotropic and give interference effects between crossed polars. The abnormal production of interference colors often of a low order, is called 'anomalous' e.g. Melilite (isomorphous mixture of two molecules that of gehlenite $\text{Ca}_2\text{Al}_2\text{SiO}_7$ and akermanite $\text{Ca}_2\text{MgSi}_2\text{O}_7$) shows blue interference color.

Michel Levy Chart: Used to determine the thickness, birefringence and order of interference of colors.

Birefringence: Light in passing through a large number of transparent minerals is split into two beams vibrating along planes that are approximately at right angles to each other. Transparent minerals, with the exception of those existing in the isometric system and amorphous minerals show this feature known as 'birefringence'.

When a beam of light passes through a birefringent mineral in certain directions it is split into two beams that follow different paths. This is called 'double refraction' e.g. transparent calcite = Iceland spar.

The difference between the least and greatest refractive indices of an anisotropic substance = Birefringence

Expressed by interference colors – the higher the color or order of color, the higher the birefringence.

Higher birefringence yields the higher color = high, med, low.

Behavior of light in Uniaxial and Biaxial crystals:

Isometric class = Isotropic substances

Isodiametric class (Tetra, Hexa)

Anisometric class (Ortho, Mono, Tri) = Anisotropic substance

Anisotropic substances

Uniaxial xls

Biaxial xls

Uniaxial xls: Hex and Tetragonal xls

Light moves in all directions with equal velocity, only in one direction i.e. parallel to the c-axis, with vibrations in all directions in the basal plane. (Different velocity perpendicular to the c-axis)

C-axis = Optic axis; only one optic axis, therefore optically Uniaxial.

When light moves in uniaxial xls in any direction other than parallel to c-axis, it is broken into two rays traveling with different velocities. One the ordinary ray vibrates in the basal plane. The other, the extraordinary ray, vibrates at right angles to it and thus in a plane that includes c-axis. Such a plane, of which there is an infinite number, is referred to as the principal section.

One ray, with waves always vibrating in the basal plane, traveled the same distance in the same time. Its surface can be represented by a sphere, and because it acts much as ordinary light it is the ordinary ray (O ray)

The other ray, with waves vibrating in the plane that includes the c-axis, traveled in the same time different distances depending on the orientation of the incident beam. If the varying distances of this, the E ray were plotted, they would outline an ellipsoid of revolution, with the optic axis, the axis of revolution.

Because the two rays have different velocities there are two RI.

+ve when O ray has greater velocity $\omega < \epsilon$, where ω = RI of OR and ϵ = RI of ER

-ve when E ray has greater velocity, $\epsilon < \omega$.

Difference between ω and ϵ is the birefringence.

Optical Indicatrix:

The relation between refractive indices and xlography can be visualized best by extending lines in all directions from the center of a xl or a xline grain with the length of each line proportional to the RI for that vibration direction. The resulting figure is known as the 'Indicatrix'.

Uniaxial Indicatrix:

The uniaxial indicatrix is a geometrical figure that is helpful in visualizing the relation of the refractive indices and their vibration directions that are perpendicular to the direction of propagation of light through a xl. For +ve xls the indicatrix is a prolate spheroid of revolution, for -ve xls it is an oblate spheroid of revolution.

The axis of revolution of the indicatrix is then proportional to ϵ , the greatest index in +ve xls and the least in -ve xls.

A study of the indicatrix shows that :

1. ω can be determined on any xl grain and only ω can be measured when light moves parallel to the optic axis,
2. ϵ can be measured only when light moves normal to the c-axis and

3. a randomly oriented grain yields, in addition to ω , an index intermediate to ω and ϵ , called ϵ' . The less the angle between the direction of light propagation and the normal to the optic axis, the closer is the value ϵ' to true ϵ .

Biaxial xls:

(ortho, mono, tri)

Because they have two directions in which light travels with zero birefringence.

Two circular sections are symmetrically placed and their radius is the intermediate refractive index β .

X – fastest, Y – intermediate, Z – slowest

When Z is the acute bisectrix = +ve

When X is the acute bisectrix = -ve

(The vibration direction in the acute angle = acute bisectrix = -ve Micas)

The vibration direction in the obtuse angle = obtuse bisectrix = +ve (barite)

Interference figures:

When properly oriented crystal sections are examined in convergent polarized light with the polarizing microscope is converted to a 'conoscope' by swinging in the upper substage condensing lens, so that the section can be observed in strongly converging light, using a high power objective (40x). The interference figure then appears as an image just above the upper lens of the objective and can be seen between crossed polars by removing the ocular and looking down the microscope tube. If the Bertrand lens, an accessory lens located above the analyzer, is inserted, an enlarged image of the figure can be seen through the ocular.

Uniaxial Int. Fig.

Biaxial Int. Fig.

Construction and use of quarter and full wave plates and quartz wedge:

- Accessory plates –
1. Full wave plate – Gypsum plate
 2. Quarter wave plate – Mica plate
 3. Quartz wedge

Function – To produce interference of known amounts and thus predetermined colors.

They are all constructed so that the fast ray (the vibration direction of the lesser RI) is parallel to the long dimension.

The gypsum plate is made by cleaving a gypsum xl to such a thickness that in white light it produces a uniform red interference color – red of the 1st order.

The mica plate is made with a thin mica flake, cleaved to a thickness that for yellow light. It yields a path difference of a quarter of a wavelength. It is thus also called the quarter wave plate $\lambda/4$.

The quartz wedge is an elongated wedge-shaped piece of quartz with the vibration direction of the fast ray (ω) parallel to its length and the slow ray (ϵ) across its length.

As thicker portions of the wedge are placed in the optical path, the path difference of the rays passing through it also increases, producing a succession of interference color. The number of orders depends on the wedge angle; the greater the angle the more orders per unit of length.

In monochromatic light, it is crossed by alternating light and dark bands.

Optic sign of Anisotropic Media

Optic sign: Uniaxial

1. Gypsum plate
2. Mica plate
3. Quartz wedge: color band in SE-NW quadrant move forward the center and disappear. At the same time in the NE-SW quadrants the colors move outward to the edge of the field = -ve

Vice versa = +ve.

In biaxial:

1. Gypsum plate
2. Quartz wedge:

Dispersion of optic axes in biaxial xls:

Dispersion is the expression of a mineral's capability to separate white light into colors of the visible spectrum. It depends on differences in indices of refraction for different wavelength of the spectrum.

The wavelength of red light is greater than the wavelength of blue light, so that the refractive index of red is less than that for blue. White light entering a medium is broken up into the colors of the spectrum, the blue color occurring nearest to the normal since it has the greatest RI, and the red the farthest away. This breaking up of white light is called 'dispersion'.

In biaxial xls all 3 principal RIs undergo dispersion that is not necessarily proportional and results in dispersive effects involving the optic angles. Dispersion introduces certain peculiarities into interference figures of biaxial xls observed in white light, These peculiarities are attributable (characteristic) to the fact that for each wave length of light there exists an indicatrix which has its own characteristic RI, optic angle and optic orientation.

An important process of dispersion in biaxial xls is the presence of color fringes (edge, periphery) on the isogyres of interference figures. These fringes may be pronounced or barely visible depending upon whether the dispersion is strong or weak. The amount of dispersion as seen in interference figures may be expressed as follows: perceptible, if the isogyres show faintly visible colored borders; weak, if a little move easily seen; strong, if very apparent; and extreme, if the color fringes cover a large part of the field of the microscope.

Dispersion of the indices of refraction in biaxial xls results in dispersion of the optic axes. The reason for this is apparent when it is considered that the optic angle, $2V$ may be computed from the indices.

Dispersion of the optic axes in biaxial xls is expressed by a formula which states whether the optic angles for red is greater or less than the optic angle for violet. These colors are chosen because they are at the extremes of the spectrum for white light and because they are the colors commonly seen in the color fringes. If $2V$ for red is greater than $2V$ for violet, the dispersion formula is $r > v$. $r < v$ expresses the reverse relationship. The violet is actually a bluish violet and sometimes almost a pure blue.

- Orthorhombic dispersion for orthorhombic xls.
- In Monoclinic xls – crossed dispersion, horizontal dispersion and inclined dispersion.

Crossed dispersion: The acute bisectrix parallels the b axis, and the obtuse bisectrix and the optic normal lie in the xlographic plane of symmetry (including a and c axis)

Horizontal dispersion: The obtuse bisectrix parallels the b axis and the acute bisectrix and the optic normal lies in the xlographic plane symmetry.

Inclined dispersion: The optic normal parallels the b axis, and the acute and obtuse bisectrices lies in the xlographic plane of symmetry.

In all three acute bisectrix figure show in white light.

In triclinic xls- Since there is no planes of symmetry in triclinic xls, it is theoretically possible for the indicatrix for each color to assume any position in a xl and dispersion of the optic axes, indices and the bisectrices produces unsymmetrical color fringes in interference figures. Usually the dispersive effects can be described only by assuming a combination of two or more types of monoclinic dispersion.